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Comparison of turbulence length scales assessed with three measurement systems in increasingly complex turbulent flows

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ABSTRACT

This paper proposes to compare turbulence length scales measured with three different experimental systems commonly used in aerodynamic measurements, namely hot wire anemometer, Laser Doppler Velocimetry and Particle Image Velocimetry, using turn-key systems from Dantec and TSI, and for three different turbulent flows: a homogeneous and isotropic turbulent flow, a homogeneous shear flow and the wake of a porous disc.

This study will show that Taylor macro scale assessment is not clearly dependent on the experimental system used, except for nonconstant shear, where the measurement volume size seems to be a critical parameter. On the other hand, Taylor micro-scale is highly dependent on the space or time resolution of the correlation and on the presence of random measurement noise. Among the three systems, only the hot wire anemometer seems to provide the right requirements to properly assess the Taylor micro-scale.

1. Introduction

Assessment of the turbulence length scales is often needed in order to characterize the properties of the turbulent flow studied. These parameters govern the mixing process in heat and mass transfers. In order to describe a turbulent flow, the Taylor micro-scale λ and the Taylor macro-scale (also called integral length scale) Λ are quantified and used as ones of the most relevant reference scales of the flow. These scales were analytically defined by Taylor [1] for a homogeneous and isotropic turbulent flow (HIT). Their definition is based on the specific shape of the space correlation functions of streamwise velocity obtained in the HIT case. In that case, a physical interpretation of these values can be proposed. However, due to the lack of alternative, these scales are extensively used even in non-HIT flows. In this case, a consensus is often accepted that while the length scales obtained by the method proposed by Taylor lose part of their physical meaning but they are considered as reference numbers, widely used by the scientific community to check the similarity of configurations. For instance, in atmospheric flows, the determination of the integral length scale present in the atmospheric boundary layer is required to classify the atmospheric dispersion processes. In non-HIT and reactive flows, the micro-scale is deduced from the macro-scale, through HIT-valid relations, to determine the turbulent combustion properties. Although this procedure is not satisfactory, it is by consensus used in the absence of better solutions.

With the exception of a few configurations that have analytical solutions, the determination of the turbulence length scales in a specific configuration is performed thanks to experimental or numerical data. Both supply space or/and time discretized information, leading to an adaptation of Taylor's definitions to discrete signals of finite length. The precision of the calculated length scales is then dependent on the averaging time, the sampling frequency, the measurement volume of the probe and the dynamic response of the system for experiments, and on the refinement of the mesh and the time step for computations. Furthermore, space correlation functions in the streamwise direction are often estimated through time correlation functions by means of the Taylor hypothesis. This is the case with hot wire anemometry (HWA) and Laser Doppler Velocimetry (LDV), which measure time series of velocity (furthermore, the LDV system has an irregular acquisition frequency, making it necessary to re-sample the time series with a regular time step to compute the correlation functions). Particle Image Velocimetry (PIV) bypasses this additional hypothesis since it supplies a space cartography of velocity. The Taylor hypothesis is extensively used but its validity depends on the flow configuration. The greatest difficulty is to choose the appropriate convection velocity. In HIT flows, the convection velocity is naturally the time-averaged velocity. However, in more complex flows, such as shear flows, the convection velocity has often been empirically assessed. In plane or separated shear layers for instance, this convection velocity is expected to be half of the mean of both reference

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velocities. In wakes (such as flows behind a circular cylinder), 0.8 of the reference velocity is consensually used. These values have been chosen in agreement with the convection properties of the coherent structures located in shear flows. Zaman and Hussain [2] stressed that using this constant convection velocity is the *least bad* solution, according to the coherent structures, but that the validity of the Taylor hypothesis is highly debatable in turbulent shear flows, in general. Despite these drawbacks, the Taylor hypothesis is universally used in experiments since no alternative to temporal measurements was available before the advent of PIV.

In this general context, the present paper will compare the integral length scales obtained from three different measurement systems, HWA, LDV and PIV (all three measurement systems are commonly used turn-key systems from Dantec and TSI), for three different flow configurations: a HIT flow, a homogeneous shear turbulent flow (HST), and the axisymmetric wake of a porous disc. The purpose was to progressively complexify the turbulent flow without generating strong coherent structures [3]. This study thereby enables comparison between different ways of obtaining the turbulent length scales, with regards to temporal or spatial measurements (the influence of the Taylor hypothesis can then be assessed), regular or irregular acquisition frequency and different measurement volumes.

The experimental set-ups for the three turbulent flow configurations will be described, as well as the three measurement systems. Comparison of the turbulent length scales obtained is performed and some conclusions are drawn.

2. Theoretical background

Taylor [1] introduced a reference length scale, called Taylor macro-scale, which is supposed to be representative of the size of the most energetic structures in turbulent flows. He proposed a relationship between this reference length scale and the distance or the time delay until the velocity fluctuations are not correlated anymore with themselves. The Taylor macro-scale is then defined as the integration of the time/space correlation functions. Indeed, these functions allow one to quantify the similarity in signals recorded at the same time, but at two different locations (space correlations) or at the same location but at two different times (time correlations), depending on the experimental tools. For turbulence analysis, streamwise space and time correlation functions of the streamwise velocity are determined from the second order moment of velocity fluctuations u' and are given by Eqs. (1) and (2), respectively:

$$R_{uu}(\xi,t)=\frac{\overline{u'(x,t)u'(x+\xi,t)}}{\sqrt{\overline{u'^2(x,t)}\,\overline{u'^2(x+\xi,t)}}} \tag{1}$$

$$R_{uu}(x,\tau)=\frac{\overline{u'(x,t)u'(x,t+\tau)}}{\sqrt{\overline{u'^2(x,t)}\,\overline{u'^2(x,t+\tau)}}} \tag{2}$$

where ξ and τ are the space and time lag, respectively. The bars in Eqs. (1) and (2) stand for the statistical averaging operator but since flows investigated in the present paper are stationary, this operator can be replaced by a time averaging operator. In steady turbulent flows, the time or streamwise space correlation function of the streamwise velocity keeps a characteristic shape: for zero time/space lag, correlation function is equal to one indicating that the signal is self-correlated. By increasing the time/space lag, the correlation function decreases progressively to zero, indicating that the shifted signal is increasingly decorrelated from the unshifted signal. This decay of the streamwise space/time correlation from one to zero represents the area where the information contained in the velocity fluctuations retains its similarity. Thus, the specific shape of this function can be correlated with the time or length scale representative of the turbulence structures involved in the flow. Indeed, its asymptotic behavior is used to define the Taylor macro-lengthscale Λ_{u_x} (or integral scale) and the Taylor macro-timescale Λ_{u_t}, by integrating the correlation function of the streamwise velocity according to the streamwise space or time lags (Eqs. (3) and (4), respectively):

$$\Lambda_{u_x}(t)=\int_0^\infty R_{uu}(\xi,t)d\xi \tag{3}$$

$$\Lambda_{u_t}(x)=\int_0^\infty R_{uu}(x,\tau)d\tau \tag{4}$$

The shape of the correlation functions for small streamwise space/time lags enables the micro-lengthscale λ_{u_x} and the micro-timescale λ_{u_t} as defined by Taylor [1] to be quantified. They are determined from the second derivative of the correlation functions when the streamwise space/time lags tend to zero (Eqs. (5) and (6), respectively) and they represent the order of magnitude of the smallest length/time scales of the turbulence:

$$\frac{1}{\lambda_{u_x}^2(t)}=-\frac{1}{2}\left(\frac{\partial^2R_{uu}(\xi,t)}{\partial\xi^2}\right)_{\xi=0} \tag{5}$$

$$\frac{1}{\lambda_{u_t}^2(x)}=-\frac{1}{2}\left(\frac{\partial^2R_{uu}(x,\tau)}{\partial\tau^2}\right)_{\tau=0} \tag{6}$$

The Taylor hypothesis, assuming frozen turbulence, fixes the ratio between the macro- and micro-length scales and the macro- and micro-time scales at the convection velocity of the turbulent flow U_c (fixed in the present study to the time-mean local velocity). The macro- and micro-length scales can then be deduced from the macro- and micro-time scales:

$$\Lambda_{u_x}(x)=U_c\Lambda_{u_t}(x) \tag{7}$$

$$\lambda_{u_x}(x)=U_c\lambda_{u_t}(x) \tag{8}$$

This convenient hypothesis is widely used in experimental studies since before the advent of the Particle Image Velocimetry, measurement techniques gave some highly time-resolved but poorly space-resolved signals. Consequently, the time scales were precisely obtained and the length scales were deduced from them, adding a uncertainty due to the applicability of the Taylor hypothesis. Nowadays, PIV has switched these signal properties and the length scales are directly computed. Nevertheless, it is common to add a time averaging operator to the computation of the length scales in order to obtain time-mean length scales $\overline{\Lambda_{u_x}}$ and $\overline{\lambda_{u_x}}$. This approach is used in the present paper.

In practice, the computation of all these functions is applied to both finite and discretized signals, whereas they were defined for infinite continuous signals. Consequently, the sampling frequency, as well as the averaging time, play an important role in the accuracy of the result. This feature will be discussed in the present paper.

3. Experimental set-up

3.1. The wind tunnel

Tests were run in a Eiffel-type wind tunnel at the PRISME Institute in Orléans, France. The square test section is $H = 0.5$ m high and 2 m long. The maximum freestream velocity is 45 m s^{-1} with a freestream turbulence intensity lower than 0.4%. The three differents types of turbulence were produced by using grids with distinct geometrical features placed at the entrance of the test section. The freestream reference velocity was fixed at $U_{ref} =$ 20 m s^{-1} for all measurements.